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SUGGESTED IMPROVEMENTS IN STEEL FOUNDRY PRACTICE

BY

LOUIS RUSSELL MANN

A THESIS SUBMITTED FOR
THE DEGREE OF MASTER OF SCIENCE

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1922

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Introduction.

It is a common belief among users of steel that where strength and toughness are requirements, the metal must be subjected to mechanical work previous to final heat treatment. In pursuance of this belief, the history of the making of some common part such as an automobile crank shaft is as follows.

The steel is poured from the furnace in which it was made into an ingot mold. After solidification the mold is removed, and the stripped ingot goes into a soaking pit to be uniformly heated to a temperature suitable for rolling. In the rolling mill the billet is worked down to a shape and size suitable for the drop-forge. These shapes are shipped to the drop-forge plant. Here another heating brings the metal to a proper temperature for the hammer, and after a series of roughing treatments, the metal assumes its final shape in the finishing die. After trimming of the web formed at the juncture of the dies, the part is ready for final heat treatment. These operations have required the use of a great deal of expensive machinery. Also a large amount of heat has been wasted in the repeated heatings and coolings.

In the majority of cases the greater part of the process cited above may be profitably eliminated. The molten

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steel from the furnace may be poured into molds which give it its final shape, and the only remaining necessary treatment is proper heat treating. By proper correlation of operations from the making of the steel through to the final heat treatment, castings can be made to have physical qualities equal to those of the best forged steels.

The war expanded steel foundry capacities far beyond normal peace time demand. At present, with business approaching a pre-war basis, this capacity is far from utilized. It is a safe prediction that as long as steel-foundrymen themselves remain blind to the possibilities of their own product, consumers will not effect any broad use of castings in new fields. In the light of what has here been said, however, possibilities appear for the steel-foundryman not only to bring about a capacity demand, but to go beyond that point to an extent undreamed of.

Two things must the steel-foundryman do to attain this end. First he must throw aside slipshod methods of production and make use of knowledge now available to produce castings which are actually as suitable for hard usage as forgings. Secondly he must conduct a compaign of education to the consumer to overcome the prejudice in favor of forgings. With the first of these necessary attainments I am here concerned.

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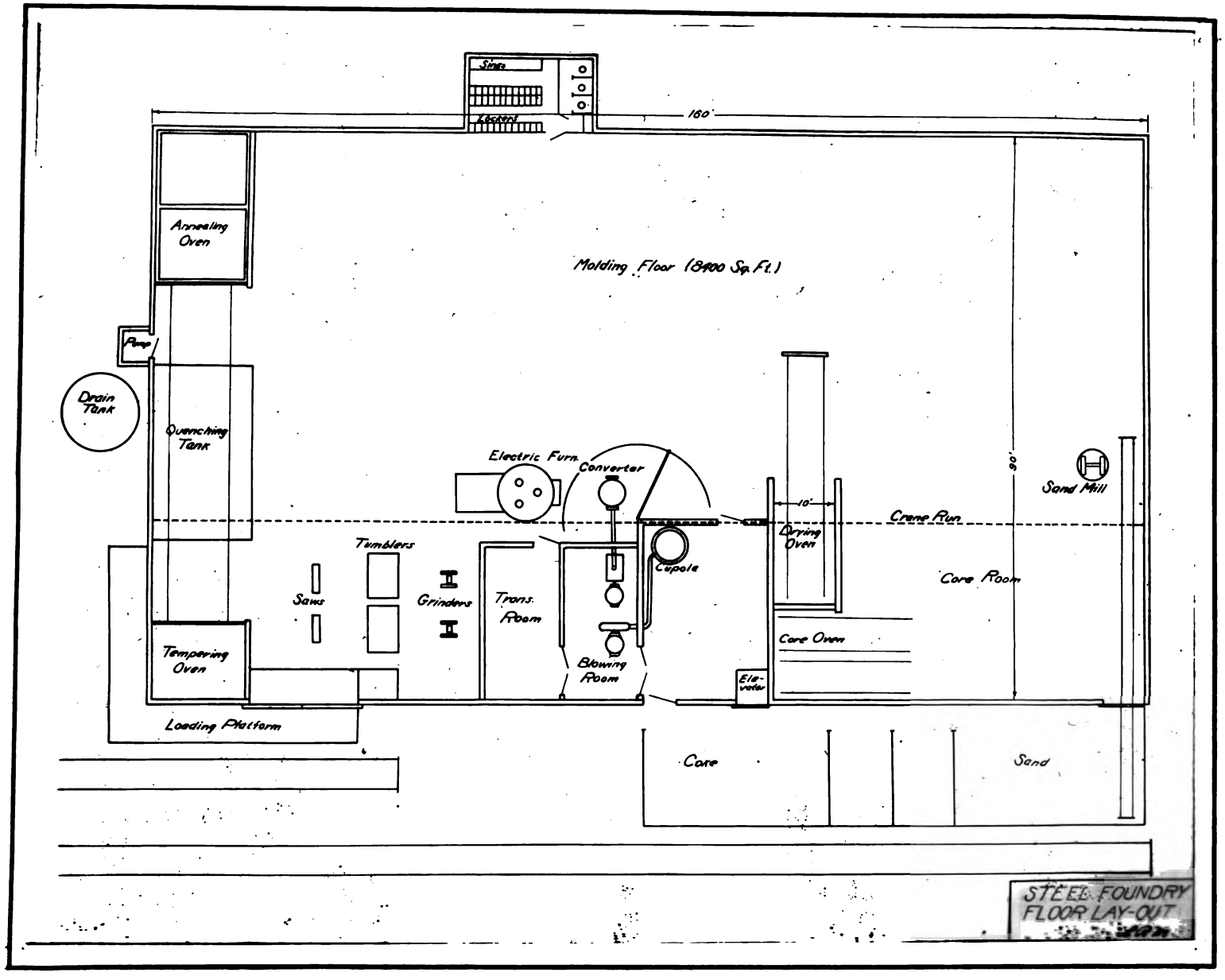

Plate 1.

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Making the Steel.

The first problem relative to the production of high grade castings lies in the making of the steel itself. The object here is to produce a metal for pouring which is capable of realizing the fullest benefit from proper heat treatment, at the same time remembering the necessary consideration of cost.

The requirements in the ladle metal are correct analysis and "dead" or thoroughly deoxidized steel. Phosphorus in excess of .04% opposes the object of future heat treatment and causes brittleness. Sulphur in excess of the same proportion causes weakness through its tendency to form an iron-sulphide network along grain boundaries. "Wild" or highly oxidized metal produces blow-holes and resulting unsoundness. The "wildness" may be eliminated to some extent by the addition of aluminum but the resulting aluminum-oxide forms inclusions in the metal, which not only reduce the metal area over any section but cause added weakness due to "notch effect".

Now the side-blown converter does not reduce the phosphorus and sulphur content, but on the contrary slightly increases the proportion of these constituents due to oxidation loss of other constituents. There may also be some increase of sulphur in the cupola. Raw material very low in these objectionable elements must therefore be used in this process, and such material commands

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a substantial price premium. Moreover converter metal does not attain the desirable degree of deoxidation.

In the electric furnace on the other hand, the phosphorus and sulphur may be removed at will. The metal as poured from the furnace is thoroughly deoxidized and lies perfectly quiet in the ladle. As far as the requirements of the metal are concerned here seems to be the ideal agent.

At this point, cost becomes a vital consideration, however. A two-ton converter easily blows two heats or four tons of steel every hour and its original cost (complete with cupola) is $15,000. As an electric furnace requires four hours time for melting and refining, it will take three five-ton electric furnaces to about equal this rate of production, such equipment costing well over $100,000. Also the heat cost for melting is much in favor of the cupola. The following analysis brings out the difference in actual operating cost of the two processes.

Converter (two-ton) producing 40 tons in a ten hour day and running 300 days in a year:

Labor-			
Charging cupola and yard,	2 men at	$3.00	$ 6.00
Cupola tender	1 man "	4.00	4.00
Vesselman	1 " "	3.50	3.50
Blower	1 " "	5.00	5.00
			18.50

Labor per ton $18.50/40	$ .46
Fuel, 1/5 ton coke at $10.00	2.00
Repairs and maintenance	.25
Power	.25
Supplies and miscellaneous	.25.
	3.21
Int. and dep. at 15% on $15,000/12000	.19
Total operating cost per ton	$3.40

Electric (five-ton) producing 15 tons in a twelve

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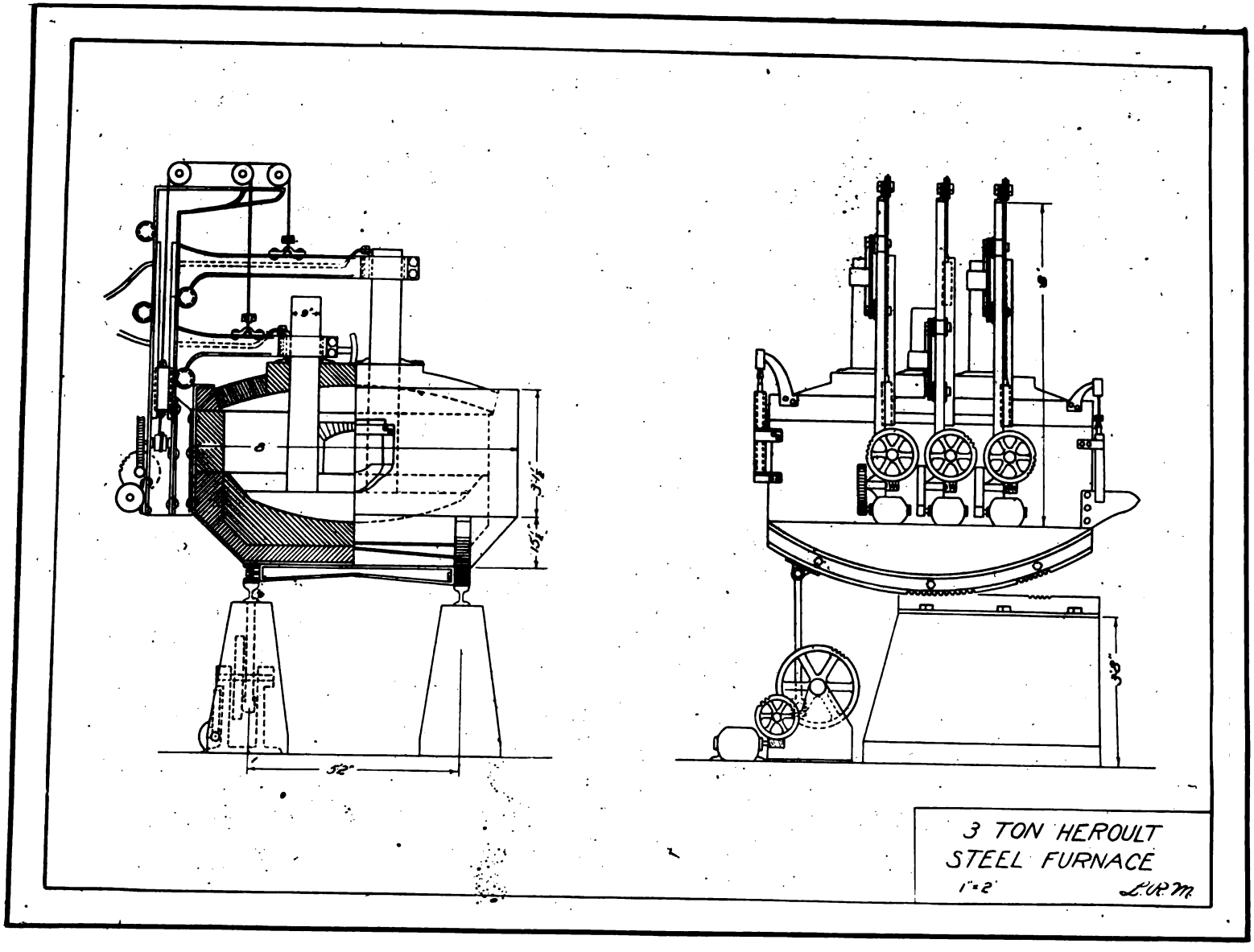

Plate 2.

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hour day and running 300 days in a year.

Labor-	
1 melter at $8.00 per day	$8.00
1 helper at 6.00 " "	6.00
1 " at 5.00 " "	5.00
	19.00
Power 800 KW/hr @ .015	12.00
Labor per ton 19.00/15	$1.27
Electrodes	1.50
Repairs and maintenance	1.00
Supplies and miscellaneous	.50
	16.27
Int. and dep. 15% on 35,000/(15x300)	1.17
Total operating cost per ton	$17.49

This cost comparison emphasizes a basic principle back of electric furnace use. The electric calorie, depending on the locality costs from three to twelve times as much as the calorie direct from carbon fuel. The equation $(T_s-T_b)/K = H$ (T_s=temp.source; T_b=temp.body to be heated; K=conductivity constant; H=heat given to body) shows where this cheaper calorie can be efficiently applied. Where T_b is low as in heating up andmelting a cold charge, T_s does not have to be high in order to have thermal efficiency, and the use of the cheaper calorie is economically correct.

From the above cost analysis it follows that the premium for the pure material for the converter charge may amount to $14.09, the difference between the two operating costs, before the converter process is as expensive as the electric for steel in the ladle. The difference in cost will usually be less than that figure, but there remains the fact that the electric furnace finishes the metal in a better condition for pouring.

All of the above stated facts, and the cost analysis above computed lead to a single conclusion. In order to be

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able to use a cheap material for the charge,and in order to have a thoroughly deoxidized ladle metal,the electric furnace should be included as a finishing process. For greatest economy,however,the preliminary heating,melting and refining should be accomplished in the cupola and converter.

Using such a duplex process,the phosphorus and sulphur limitation of the converter process disappears,as does the objection to the oxidized condition of the finished metal. The amount of power required in the electric furnace is much smaller,and the high"peak load"necessary to start a cold charge in the electric furnace is greatly reduced. The shorter time during which the metal remains in the expensive electric furnace also causes a substantial decrease in the depreciation and interest item. A basic electric furnace can refine six heats in a ten-hour day,so a four-ton unit supplied by a two-ton converter will produce twenty-four tons of ladle metal in that time. A cost analysis of such an arrangement is as follows.

Labor-		
1 melter at $7.00	$7.00	
1 helper at 5.00	5.00	
	12.00	
Cost of metal from converter		$ 3.40
Labor per ton 12.00/24		.50
Power,300 KWhr @ .015		4.50
Electrodes		.35
Repairs and maintenance-		.25
Supplies and miscellaneous		.50
		9.50
Int.& dep. 15% on $35,000/(24 x 300)		.73
Cost per ton of ladle metal		$10.23

The premium paid for high grade charge for the converter operating alone will generally amount to more than the difference between $10.23 and $3.40,so even neglecting the superior quality of the ladle metal,here would seem to be the more desirable process. Starting with the same impure material and finishing

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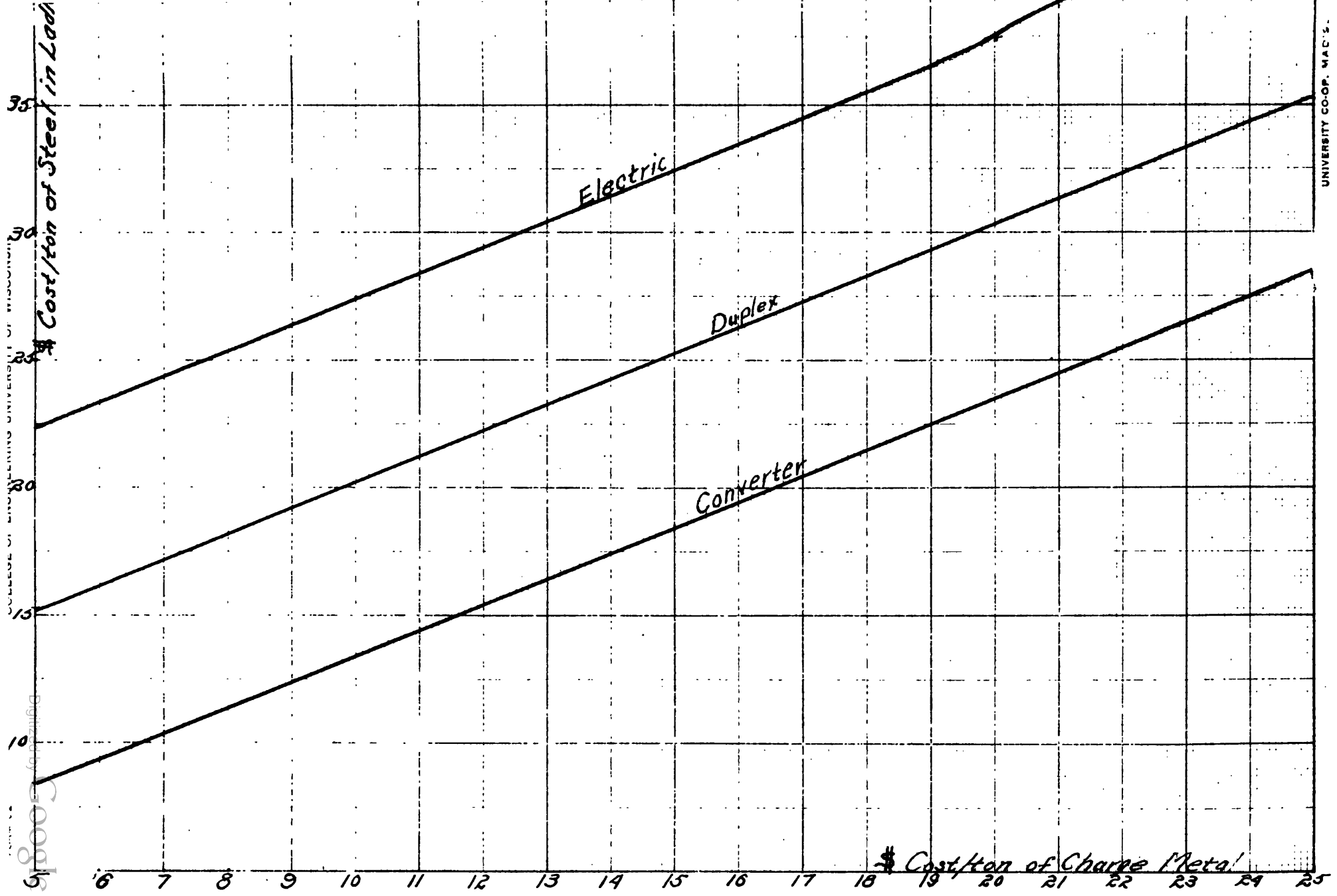
Electric
Duplex
Converter
$ Cost/ton of Charge Metal
5
6
7
8
9
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with metal of the same quality the duplex process effects a saving of nearly seven dollars per ton over the electric furnace operating alone.

Knowing at any time the cost of low phosphorus and sulphur raw material necessary for the converter alone, and applying this figure to the abscissae scale of the accompanying chart (fig 1), the corresponding ordinate gives the cost per ton of the ladle metal. The cost of ordinary material for the electric or duplex process applied in the same way will give the ladle cost of steel made by either of these methods. Variations in cost of coke, electric power etc. in different communities would of course displace these curves to some extent, but such a chart computed from local conditions would be valuable in a steel foundry.

In the molding itself, new problems are every day met, and are well solved by men skilled in the trade. The possibilities of very greatly improving the physical qualities of the casting as taken from the mold, however, are too little considered. The reasons for the weakness of the steel as taken from the mold and after being subjected to ordinary heat treatment, and the general considerations regarding treatment which will greatly improve quality will be next discussed.

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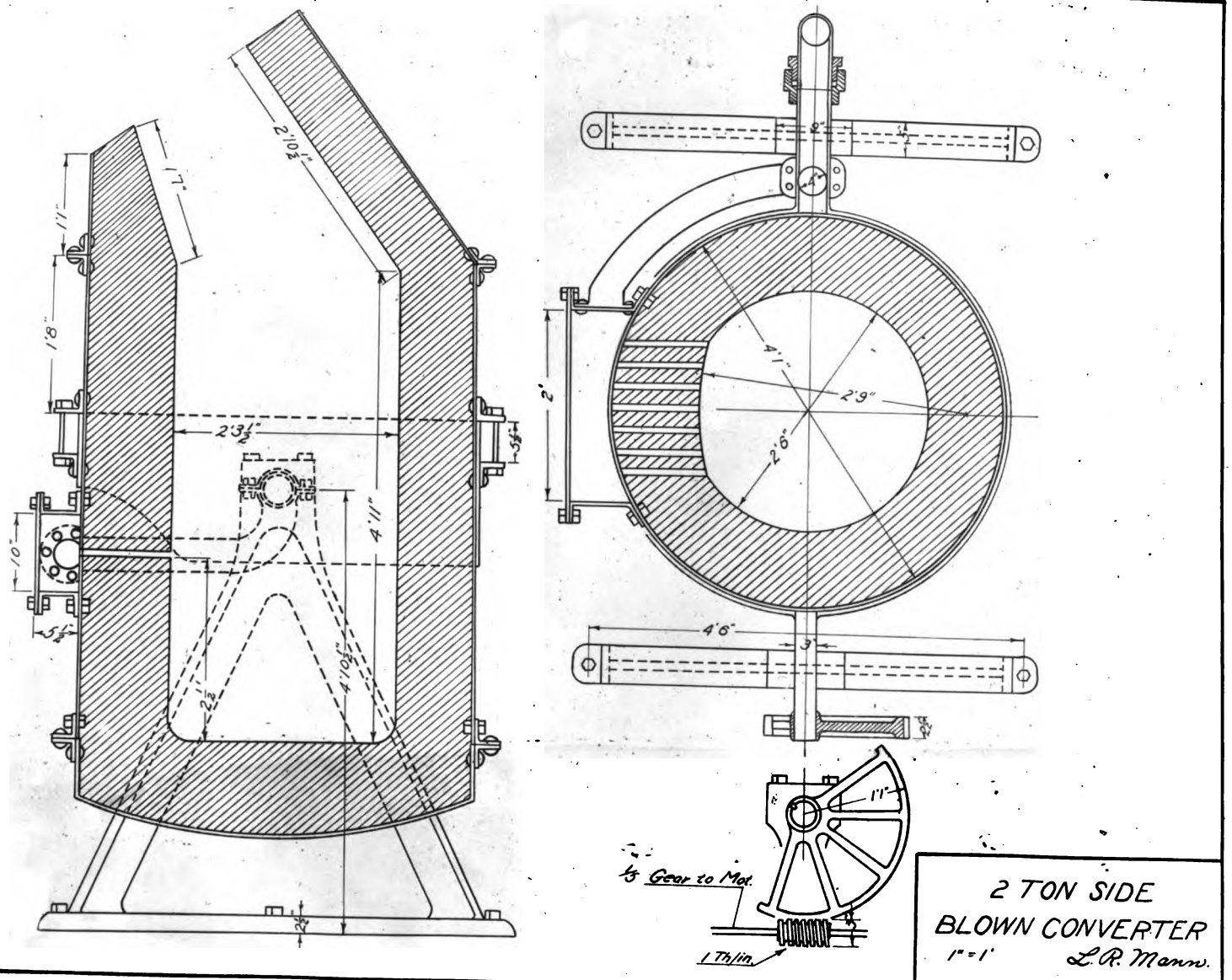

Plate 3

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Heat Treatment.

Castings have approximately the same specific gravity as forgings, so considering castings and forgings of the same analysis, any superior qualities found in the latter must be primarily due to a more suitable internal structure.

Hot work followed by proper heat treatment gives to medium carbon steel a very fine-grained structure, and tiny particles of ferrite embedded in a sorbite matrix are completely isolated by sorbite. In an untreated casting the ferrite is found in a network or at least in a broken reticule. Subjected to ordinary heat treatment this network is only slightly affected and it remains in sufficient degree to differentiate cast steels physically from forged steels.

Without inquiry into the causes underlying the manner of ferrite separation, this has for long been accepted as an unchangeable condition.

Recent theory tested by experiment shows that the course of secondary crystallization of the ferrite as the temperature falls through the critical range is dependent on the degree of homogeneity existing in the austenite from which the separation takes place. A preliminary treatment to bring about homogeneity in the austenite is then necessary in order to obtain an ideal structure in cast metal.

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To show why the austenite lacks homogeneity the course of cooling in an alloy of the solid solution type will here be traced.

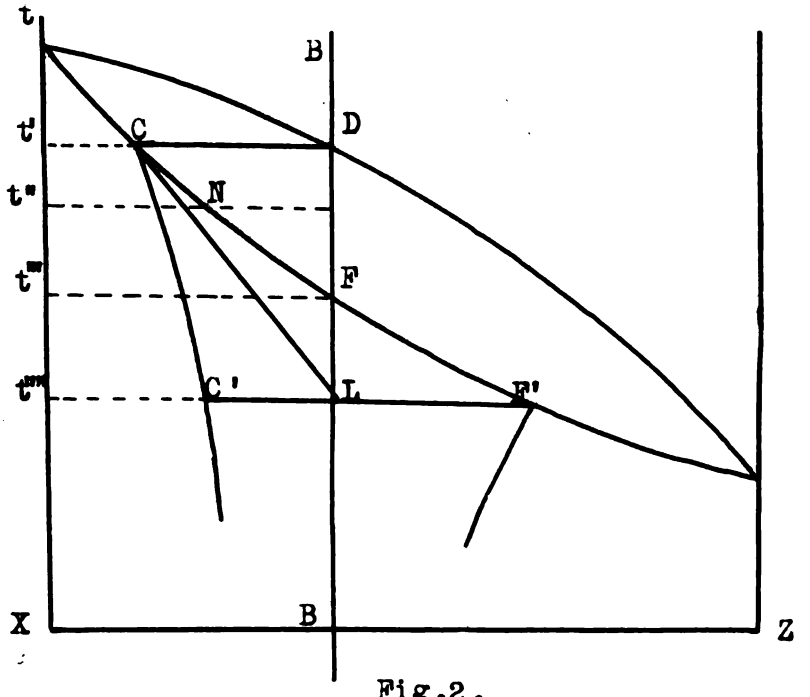

Fig.2.

Consider XZ any binary alloy diagram in which the components are soluble in all proportions. Now an alloy of compositon B, being completely molten at temperature t, on cooling to t' starts to separate out crystals of composition C. On cooling, the composition of the solid precipitating out follows the solidus line CF, so that at temperature t" the separating solid is of composition N. Thus the nucleus of composition C is the center of a crystal consisting of layers of XZ solid solution ever becoming richer in Z. Now should diffusion take place with infinite rapidity from the outer region of higher Z concentration toward the center, the difference in concentration between succeeding layers will disappear, and the line CF will at all times represent the composition of the entire solid portion. When t''' is reached, the composition of the solid separating coincides

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with the alloy composition,and the entire mass becomes solid.

Diffusion in a solid actually takes place,however,far too slowly to have the above ideal condition even approached in practice.

Diffusion acts just rapidly enough so that the nucleus of composition C becomes slowly enriched in Z,its composition following the line CK as the temperature falls. CF represents at any temperature only the composition of the surface of the crystal. Line CL follows the average composition of the separating crystal,and as the average composition of solid separated out reaches the alloy composition,final solidification occurs at temperature t"". The mass then consists of crystals whose internal composition varies from composition C' at the nucleus to F' at the periphery.

Throughout the range of steel composition and above critical temperatures the iron-carbon diagram is of the solid solution type,in which cooling occurs as above described. As a result,the austenitic crystals making up the mass vary individually in composition from a low carbon nucleus to a periphery high in carbon (also high in phosphorous).

The importance of this fact lies in the resulting effect on the manner of the separation of the ferrite as the temperature descends through the critical range.

Referring now to the iron-carbon constitution diagram, through the upper range of primary crystal separation a condition occurs just as explained in detail regarding the solid solution alloy XZ. As a result,at temperature t the austenite consists of crystals having a low carbon nucleus of composition C'and a high-

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er carbon periphery of composition F'. At an ordinary rate of cooling, diffusion has time to lessen this difference of composition but very little, so that the low carbon nucleus reaches the temperature (t') at which ferrite starts to separate out some time before the periphery reaches the A3 line at temperature t".

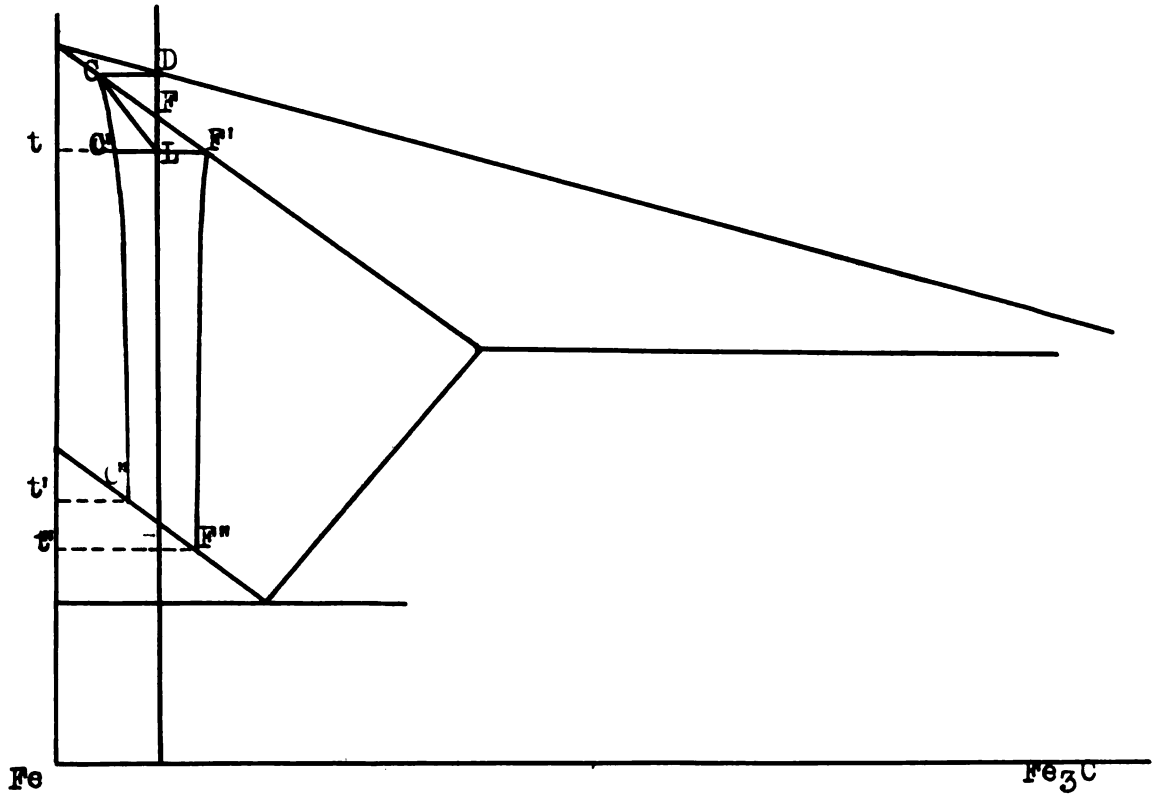

Fig.3.

Thus the nucleus of the primary crystal determines the nucleus of a ferrite crystal, and the ferrite congregates around a predetermined number of centers. The result is that ferrite accumulates in masses which touch in many places and form a ferrite network.

Considering a hypothetical case assume now that the austenite is perfectly homogeneous. The temperature of first ferrite separation is then reached by the entire mass at the same instant. A multitude of nuclei then form at random throughout the mass, and in the resulting structure tiny ferrite crystals will be

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.4 Carbon steel as cast, showing ferrite segregation and network. (x 100)

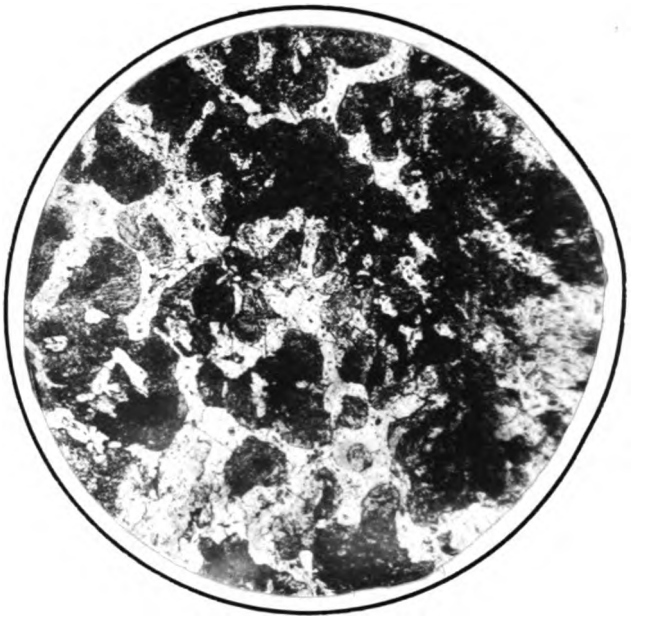

Fig.4.

.3 Carbon steel as cast. (x 100)

Fig.5.

.3 Carbon steel oil quenched after heating for one hour at 825 °C. (x 100)

(Nitric acid netch)

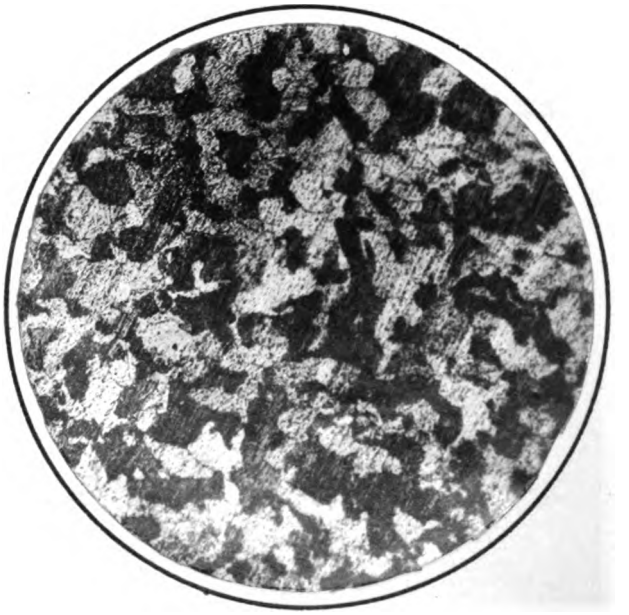

Fig.6.

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uniformly distributed. In steel of such structure are found in the highest degree, the combined qualities of strength, ductility and shock resistance.

Now while the ideal condition of a perfectly homogeneous austenite can never be completely realized in practice, such a close approximation may be obtained as to produce in cast steels a structure similar to that found in forgings. The necessary treatment consists in subjecting the steel to a temperature considerably above the critical range for a long enough time to permit the process of diffusion to approximately equalize the composition. The steel should then be slowly cooled to a temperature just above the critical range. Rapid cooling through the critical range then supplements the effect of the homogeneity treatment in effecting the dispersion of the ferrite. Quenching leaves the metal in a state of internal strain and a reheating or "drawing" is necessary to eliminate this. The structure of the eutectoid matrix is a function of the temperature at which this final operation is carried on, and in order that the eutectoid may consist of sorbite (unresolved pearlite) the "drawing" should be done at a temperature of 550°C.

Figs. 4 and 5 reproduce at 100 diameter magnification the microstructures of steels of .3 and .4 carbon content respectively. In both samples the ferrite (light) is agglomerated in large crystals forming a practically continuous network. As ferrite has a tensile strength of only 36,000#/in^2 it is no wonder that such steel has inferior qualities. The properties of a .3 carbon steel in such condition are about as follows.

Tensile strength-------60,000#/in^2

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Elastic limit--------35,000#/in^2

Elongation----------12%

Reduction of area----------5%

The impact test, the importance of which is generally underestimated, shows very low shock resistance for such metal.

An ordinary method of heat treatment in the steel foundry is to simply heat the castings to a temperature slightly above the critical range, and allow them to cool slowly. It is a common belief that such treatment reduces the grain size and is of considerable benefit. The austenite from which the second separation of ferrite takes place is substantially unaltered from its original condition, and it is hard to see why this treatment should be of material benefit, outside of a tendency to lessen internal strains incurred during the first cooling. Even when the steel is quenched in oil after such a reheating there is but little alteration of the original ferrite network. Fig. 6, which shows the microstructure of a specimen so treated, brings out the truth of this statement. Average figures for the properties of a .3 carbon steel subjected to such ordinary treatment follow.

Tensile strength-------65,000#/in^2

Elastic limit----------38,000#/in^2

Elongation----------15%

Reduction of area------10%

The impact resistance is also slightly increased.

It becomes evident that ordinary treatments do not give to castings properties comparable to those of good forged steels, and in the large interlocking grains of ferrite can be seen the reason.

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.3 Carbon Steel held four hours at 900°C and slowly cooled.
(x 100)

Fig.7.

.3 Carbon steel held four hours at 900°C, cooled slowly to 825° and oil quenched.
(x 100)

(Nitric acid etch)

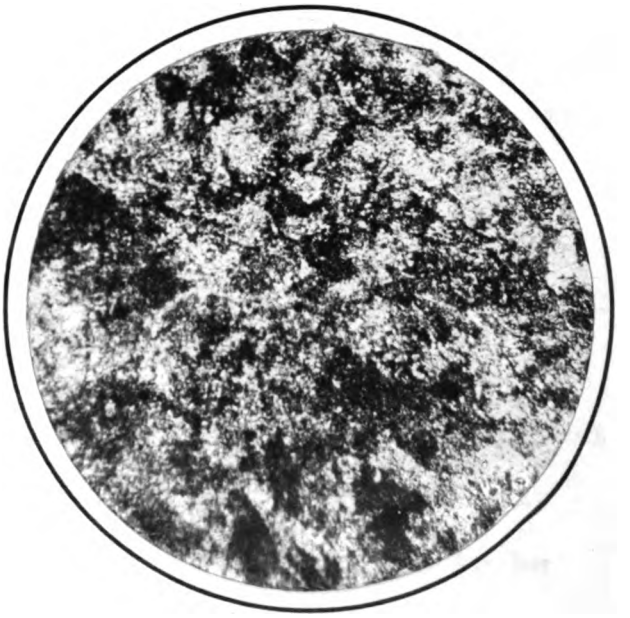

Fig.8.

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The remaining micrographs show the striking structural changes brought about as a result of obtaining homogeneity in the austenite.

Figs.7 and 8 picture the results of a preliminary treatment which has been only partially effective. In both cases the steel was held for five hours at 900°C. Specimen 7 was furnace cooled, enough power having been left on so that the descent through the critical range required two hours. The ferrite grains are still rather large, but the result of the treatment is seen in their independence and random placing. The specimen shown in fig. 8 was oil quenched through the critical range. The grain size is well reduced, but the effect of yet insufficient homogeneity of the austenite is seen in the tendency of the ferrite to localize in distinct areas.

Figs. 9 and 10 picture the effects of a homogeneity treatment as stringent as would be expedient in practice. Both specimens were heated seven hours at 950°C. Specimen 9 was slowly cooled and although the ferrite thus had opportunity to dispose itself at will, it is found to be well distributed and the grains are reduced in size and independent. Fig.10 shows the effect of quenching in oil after a sufficient preliminary treatment. All traces of continuity in the ferrite have disappeared and the grain size is minute. The structure corresponds to that of the best forged steels. In testing cast steels of similar carbon content, Giolitti showed the following properties to be obtainable with such method of treatment.

Tensile strength------90,000#/in^2

Elastic limit---------63,300#/in^2

Elongation-----------24%

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.3 Carbon steel held for six hours at 950°C and slowly cooled.
(x 100)

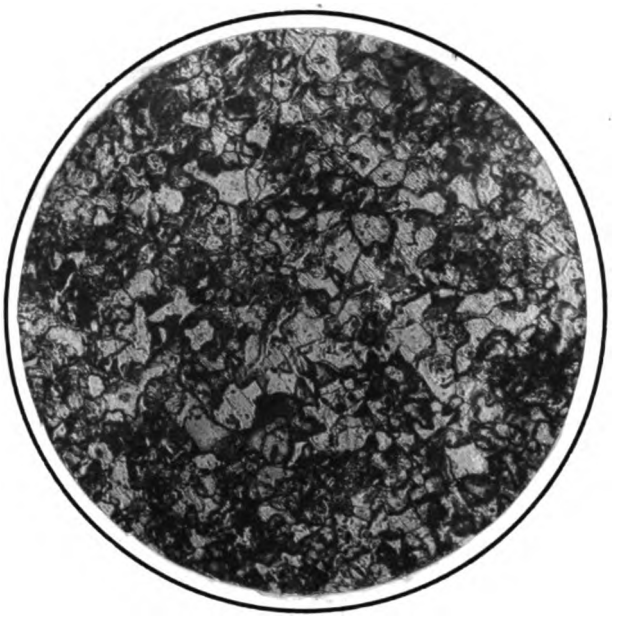

Fig.9.

.3 Carbon steel held six hours at 950°C, cooled slowly to 825 and oil quenched.
(x 100)

(Nitric acid etch)

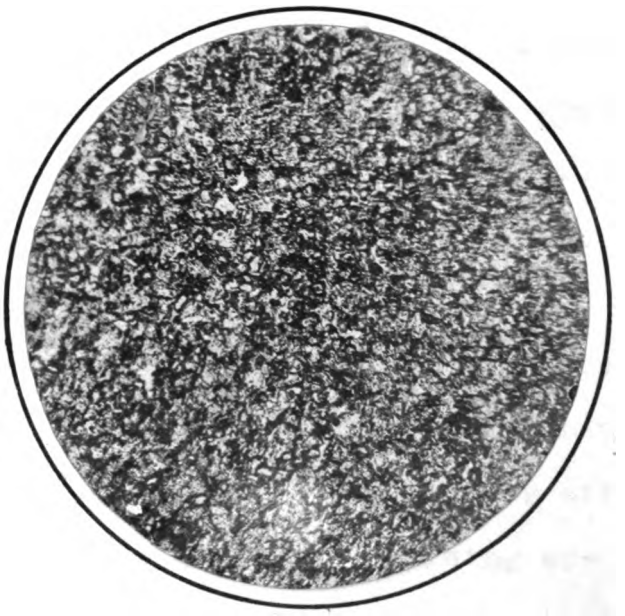

Fig.10.

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Reduction of area------40,5%

He also obtained a tensile impact resistance of 135 kg.-m. as compared to 132 kg.-m. in a properly treated forging of the same carbon content.

The steel foundry is in no way limited to the use of plain carbon steels in making castings. Alloying elements can be used with the same beneficial effects as in forgings. An alloy with from two to three percent nickel properly heat treated shows properties about the same as a forged nickel steel. The same general considerations apply in the heat treatment as in ordinary carbon steel. The effect of the alloying element is twofold. In solution in the ferrite it strengthens and toughens that element,and it also tends to increase the number of ferrite nuclei appearing as the metal on cooling reaches the critical range.

The psychological effect of one casting easily broken and showing a coarsely crystalline fracture may destroy the goodwill brought about by a hundred good ones. Proper heat treating of all the castings in the furnace requires closer attention to its operation than most furnaces are given. Too much credit is often given to the ability of the eye to determine temperature,or else the temperature indicated by a single thermocouple is accept- as the temperature of the whole furnace. Couples themselves are inexpensive and several can be used with a single recording apparatus. The results of careful temperature control in the heat-treating furnace will become apparent when the castings are put into use.

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Conclusion

The electric furnace is invaluable in the steel foundry, its use enabling the employment of low grade raw material and the finishing of the steel in ideal condition for pouring. It is most economical,however,when confined to the finishing of the metal,the steel being melted and prepared in the cupola and converter.

Castings can be produced having properties as good as those of forgings,but ordinary annealing treatment does not make them as good. Preliminary heat treatment is necessary,in order that the later treatment through the critical range will effect the proper arrangement of internal phases to lend strength and toughness. Improvement in practice in operating heat treating furnaces is here an added consideration.

Industrial inertia is also operating to keep castings out of the acclaimed field of forgings. Utilization and propagandizing of the facts herein set forth should bring about a reversal of this condition.

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Approval.

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Professor of Metallurgy.
Title

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